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Timing of goal-directed hitting: impact requirements change the information–movement coupling

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Abstract In hitting, performers are found to adapt to the approach speed of the ball, i.e. they tend to initiate their movement at a shorter time before contact for faster approaching balls. A change in movement time is always accompanied by a change in movement velocity when the movement trajectory is kept constant. Hence, a fast-approaching ball might induce high impact velocity that is in conflict with low impact constraints, such as propelling the ball towards a near goal. In this study we investigated the capacities of participants to perform one-dimensional hitting movements in the frontal plane to balls approaching on a head-on collision course. The temporal precision (i.e. ball approach speed: 1, 1.5, and 2 m/s) and impact requirements (i.e. No-Goal, Near-Goal, and Far-Goal) were manipulated to examine the influence of task constraints on the temporal regulation of a stroke. The results showed that timing and speed were significantly affected by ball approach speed when the hit was not directed to a goal. In contrast, no speed-coupling and a constant time-to-impact strategy were found when impact velocity was constrained (i.e. aiming for a near goal). We were particularly interested in the nature and relation of information sources and timing patterns of movement initiation. Therefore, the relation between the time evolution of three optical sources related to the approach of the ball and the observed patterns of swing onset were evaluated quantitatively. The analyses revealed that a viable explanation for the two observed qualitatively different onset patterns of the swing is a regulation based

on the absolute rate of expansion or a co-varying variable. The flexible adaptation of timing to impact constraints may be realized by an adjustment of the critical region of this optical variable.

Keywords Hitting · Impact requirements · Temporal precision · Timing · Visual information · Human

Introduction

Skilful performance of interceptive actions, such as hitting, is fundamental to success in many ball games. The main objective of a successful stroke is to make contact with the ball at a particular place and time, and to transfer energy to the ball in order to transport it with a certain velocity in a particular direction. Therefore, precise coordination between visual information about the ball's trajectory and the effector movement is necessary to prepare for impact. To many researchers, interceptive actions have represented a useful vehicle for developing theoretical understanding of the relationship between information and movement in goal directed behaviour. To understand processes of information based regulation of interceptive actions, it is relevant to ask what visual information actors pick up and how they use it to satisfy the spatio-temporal task constraints of hitting.

Lee and co-workers have provided a host of data, all in support of the notion that a sole variable τ , i.e. the inverse of the relative rate of optical expansion, is used to regulate all interceptive actions (Lee 1976; Lee and Reddish 1981; Lee et al. 1983). This optical variable directly specifies the time it takes an object to reach the observation point (i.e. the time-to-contact, TTC) given a constant approach velocity. Fitch and Turvey (1978) argued that gearing initiation to a critical value of TTC could easily control the timing of a swing with constant duration. Evidence for the existence of constant swing duration comes from a number of interceptive sports that involve the control of force at impact, notably baseball batting (Hubbard and Seng 1954), squash (Wollstein and

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Abernethy 1988), table tennis (Tyldesley and Whiting 1975), and field hockey (Franks et al. 1985). However, in recent hitting experiments, participants were found to adapt their movement time to the approach speed of the ball (Gray 2002; Tresilian and Loneragan 2002; Tresilian et al. 2003). They tend to initiate their movement at a shorter time before contact in response to a faster approaching ball. These effects of ball speed on timing show that participants often do not use critical values of information sources that specify TTC to regulate swing initiation. Instead they may use information such as the absolute rate of expansion (Michaels et al. 2001) and the rate of constriction of the gap between effector and ball (Caljouw et al. 2004).

Of particular interest and complexity is the incredible degree of temporal precision that is necessary for a successful stroke. The margin of timing failures is extremely small, as evidenced in studies of catching and hitting. For instance, in the case of balls travelling with a speed of about 10 m/s, the precision with which the grasping action of the hand must be timed is estimated to be in the order of 16 ms, which is the time it takes the ball to travel from the extended flexing thumb and index finger tips to the point at which the ball is held (Alderson et al. 1974). The accurate timing of a cricket stroke is even more demanding, it can only have a margin of failure of around 2.5 ms (Regan 1997). With one of the most remarkable aspects of hitting being the precision with which interceptions are timed, it is perhaps not surprising that most emphasis has been on the temporal regulation of interceptive actions. On the other hand, a tennis player could organize the most beautifully timed pattern of movements, but if he smashes too hard the ball will be out and he loses the point. In hitting, the ball is received and sent away in the same movement. Hence, the actor has to ensure that the implement (or hand) travels with the right velocity at the moment of contact to provide an appropriate amount of kinetic energy to the ball. The importance of force control at contact, whilst recognized in key definitions about the coordination process in interceptive actions (Savelsbergh and Bootsma 1994), is hardly addressed in studies of interceptive actions. To fill the existing gap, we aim to study the timing of hitting in relation with force control at the moment of impact.

From Newtonian physics, we know that a change in movement duration is always accompanied by a change in movement velocity when the movement amplitude is constant. Accordingly, participants adjust their interceptive movement to ball approach speed by adjusting the timing as well as the movement velocity. In several hitting experiments it was found that participants increase their movement velocity to intercept faster approaching objects (e.g. Brouwer et al. 2000; Smeets and Brenner 1995; Tresilian and Loneragan 2002; Tresilian et al. 2003). It is suggested that this strategy is adopted to maximize the likelihood of success. Interception of faster approaching objects requires more temporal precision and it was found that temporal precision increases as movement time decreases (Tresilian and Loneragan 2002; Tresilian et al.

2003). Hence, it was concluded that participants adopt a strategy of speed-coupling to increase temporal accuracy. However, demonstrating a correlation between movement velocity and temporal precision does not constitute conclusive proof for a causal relation.

If a fast ball induces high movement velocity of the stroke, it will probably also induce high impact velocity, and hence the ball will land further away from the interception point¹. By enforcing the distance to be covered by the ball after contact (i.e. goal distance), a conflict can be created between the demands of ball speed and impact requirements in hitting. A fast ball induces high movement velocity, and hence high impact, which may contradict with low impact constraints such as the requirement to propel the ball towards a near goal. In an experiment where participants had to propel balls approaching with different speeds towards near and far goals, it was found that participants were able to adapt their movement velocity to the distance to be covered (Fayt et al. 1997). At the same time, a significant effect of approach speed on movement velocity was found, suggesting that speed-coupling is a persistent but mouldable phenomenon.

In the first part of the present experiment we aim to assess how participants deal with temporal constraints imposed by ball approach speed. The task is to perform one-dimensional hitting movements over a fixed distance in the frontal plane to balls approaching with different constant speeds on a head-on collision course. Several studies showed speed-coupling in hitting, but the primary interest in this study was to investigate how speed-coupling is accompanied by the use of optical information sources to time the initiation of the swing. The other objective of our study was to evaluate the effects of impact requirements. In part two of the experiment, participants were required to propel the approaching balls that approach with different speeds to specified goals at different distances. We expected that enforced impact requirements would result in a diminishing of the speed-coupling effect. The main novel scientific value of this study is in determining how this modulation of speed-coupling is accompanied by an adaptation in the information-based timing of movement initiation. Adaptation in timing patterns of swing onset might be provided either by a change in the nature of the information sources used to time the initiation of the swing or by a recalibration of the way in which an information source is used to initiate the swing.

¹Since, impact velocity (V_{contact}) is proportional to the kinetic energy (E_k) that a moving effector (with constant mass M) transfers to the ball at contact (i.e. $E_k = 1/2 \times M \times (V_{\text{contact}})^2$), the distance traveled by the ball after contact will depend on the speed of the effector at contact.

Methods

Participants

Nine participants (two men and seven women) volunteered in the present experiment. The age range was 20 to 29 years (23.1 ± 2.7). They were right-handed, reported normal or corrected-to-normal vision and had stereoscopic vision in the normal range with assessed stereoacuity of at least 40 s/arc as determined with the stereopsis test (Titmus Optical Inc., Petersburg, VA, USA). This study is part of an ongoing research program that has been approved by the institutional ethics committee. Four participants assisted in the data collection, all others were naïve to the purpose of the experiment.

Apparatus

The ball (diameter 7.5 cm) was transported with one of three constant velocities (1, 1.5, 2 m/s) over a fixed spatial trajectory with the BallTrAp system (cf. Bennett et al. 1999). The hitting device consisted of an oblong object (2.5 cm wide) attached on an aluminium rod mounted on a trolley. The trolley could be displaced in one-dimension along an aluminium trackway, which was positioned orthogonal to the trajectory of the ball (see Fig. 1).

On the left side of the participant, in line with the hitting trackway, two goals (30 cm wide) were projected on the ground (135 cm below the interception point). The centres of the near and far goal were positioned 55 and 105 cm, respectively, along the fronto-parallel axis from the interception point.

During the experiment participants were wearing liquid-crystal glasses (Plato System P-1), which opened when the ball was 1.95 m (SD 14 cm) from the interception point. A 3-D-motion analysis system (one Optotrak camera unit with a sampling rate of 200 Hz) was used to register the positions of three infra-red light-emitting diodes (IREDs), one fixed to the hitting device (on the rod just beneath the oblong object), one to the liquid crystal glasses, and one to the approaching object (on the moving rod just above the point where the ball was attached). The 3-D positions of the IREDs were filtered with a second-order recursive Butterworth low-pass filter, with a cutoff frequency of 10 Hz.

Task and procedure

Participants had to perform a one-dimensional hitting movement in the frontal plane to a ball approaching on a head-on collision course (cf. Fig. 1). At the start of each trial, the participants were asked to place the rod at the start position, 30 cm from the interception point. In the first part of the experiment the impact force that participants had to apply to the ball at the moment of contact was unconstrained. Subsequently, in the second part of the experiment participants were

required to hit the ball towards different specified goals. Before the experiment started participants practiced until they were able to hit the ball four consecutive times for each approach velocity (1, 1.5, and 2 m/s) separately. We instructed the participants to simply hit the ball in an ongoing movement after the glasses opened. We did not inform them about the required landing position that would be introduced in the second part of the experiment.

After practicing, the experiment started with a block of 36 trials divided into three blocks of 12 trials, containing four trials for each velocity, presented in random order. After a short break participants were required to propel the ball to the goals. The two blocks of trials in which participants aimed for the near and far goal, each consisted of 36 trials with the three different ball approach speeds presented as in part one of the experiment. The two blocks of goal conditions were counterbalanced, four participants started to propel the ball to “Near-Goal” and the other five to “Far-Goal”. After each trial the experimenter informed the participants about the position of the ball relative to the goal; specifically, they were told whether the ball landed in front, behind or within the target area. Besides the given verbal feedback, participants could also see for themselves the goals and the place where the ball landed. We chose not to counterbalance the “No-Goal” and “Goal” conditions in order to prevent participants from being able to persist in hitting the ball to the same landing location when no specific impact demands were imposed anymore.

Analyses

First, we calculated the number of balls missed per condition. This amount was expressed as the percentage of misses per condition. Second, the movement time and the impact velocity of the hit were calculated from the position and velocity profiles of the effector. The movement time is the time between the moment of hit onset and the moment of impact. The moment of hit onset was defined as the time at which the effector approached the object with 5% of the peak velocity (i.e. maximum velocity attained by the effector), and the moment of impact was defined as the moment of minimum distance between ball position and effector position. The impact velocity was determined from the velocity profile of the effector at the moment of impact.

After assessing the results qualitatively, we performed detailed analyses of the critical values of three optical variables related to the approach of the ball (see Fig. 2): (1) The angle subtended between the edges of the ball and the point of observation (i.e. φ), (2) the absolute rate of change of this angle (i.e. $\dot{\varphi}$), and (3) the inverse of the relative rate of optical expansion [i.e. $\varphi/\dot{\varphi} = \tau(\varphi)$]. We did not examine binocular variables, such as the (relative) rate of disparity, or variables related to the position of the end-effector, such as the (relative) rate of constriction of the gap between effector and ball, because these variables are proportional to the to-be-analysed variables before the moment of movement initiation and therefore will not predict different timing patterns. Since there is no a priori reason to assume that the participants exploited identical sources of information, let alone similar critical values, each participant will be considered individually. To analyse the optical variables, we used the same method as presented in previous studies (Caljouw et al. 2004; Benguigui et al. 2004; Michaels et al. 2001). First, the time-evolutions of the optical angles were computed using the 3-D position profiles from the ball and the point of observation. The measured trajectory of the ball was extrapolated according to a first-order polynomial fit. The moment of contact between the hitting device and the ball was defined as time zero. The exact point of observation was reconstructed from the IRED located between the two eyes.

Values of φ , $\dot{\varphi}$, and $\tau(\varphi)$ were calculated for each trial at the moment of hit onset. One cannot expect the values of the used optical variable at onset of the movement to be the same; they may converge to a critical region of values in the past. Therefore, the values of all these different optical sources were calculated at visuo-

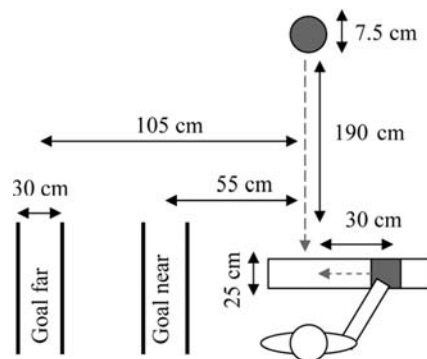


Fig. 1 Schematic overhead view of the experimental set-up. The ball approached at eye level on a head-on collision course

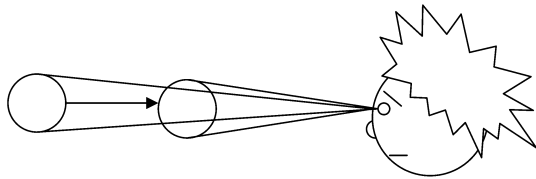


Fig. 2 The optical size of an object (i.e. visual angle φ) increases with approach

motor intervals before onset of the hit, ranging from 0 to 300 ms, using intermediate steps of 10 ms. This was done for each trial. Finally, for each optical variable, at each visuo-motor interval, simple regression analyses were conducted to establish the correlation between the optical values and ball velocity. If, for example, φ is the variable on basis of which the onset of the hit is controlled, then it might be possible to point out a region preceding the moment of initiation in which φ is independent of approach velocity. In other words, an informational value lying within the critical region is discerned when the regressions between the optical values and the ball velocities at a particular visuo-motor interval result in a non-significant regression coefficient. Interpretation of a non-significant regression coefficient is difficult because it may indicate a zero slope of the regression line or it may indicate that the different approach velocities do not explain the majority of the variability of the optical variable. Therefore, we introduced an additional criterion to discern the critical region, besides a non-significant regression coefficient, the coefficient of variation, i.e. the ratio of the standard deviation over the mean value (Wagner 1982) was not allowed to exceed the 25%. We assumed the visuo-motor interval corresponding to the lowest r^2 within the critical region to be optimal.

Results

For each condition both the percentage of balls missed and the intra-subject means and standard deviations of all dependent variables were calculated. To test the combined effect of impact requirements and temporal precision requirements, the mean values for all dependent variables were submitted to a 2×3 [(Target: Goal versus No-Goal) \times (Speed: 1 m/s, 1.5 m/s, 2 m/s)] analysis of variance with individual repeated-measures on both factors (ANOVA). To gain more insight into the effect of target position, a 2×3 [(Target Position: Near-Goal versus Far-Goal) \times (Speed: 1 m/s, 1.5 m/s, 2 m/s)] ANOVA was obtained for all dependent variables. In the case that the sphericity assumption was violated (i.e. epsilon < 1.0), Huyn-Feldt adjustments of the P -values are reported. Post hoc comparisons were conducted with Tukey's HSD test ($P < 0.05$).

Hits and misses

In the entire experiment only 7.1% of the balls were missed (69 out of 972 balls). In the first part of the experiment (not aiming towards a goal) 10.5% were missed (34 out of 324). In the second part of the experiment 5.4% of the balls were missed (35 out of 648), with respect to the two target positions combined, with 6.5% (21 out of 324) and 4.3% (14 out of 324) of the balls being missed in the conditions Near-Goal and Far-Goal, respectively.

The ANOVA that tested for the effect of impact requirements and temporal precision revealed significant main effects for Target ($F_{(1,8)} = 25.464$, $P < 0.001$) and Speed ($F_{(2,16)} = 7.392$, $P < 0.01$). As described above, more balls were missed when participants did not aim to a target. This is probably due to the fact that the No-Goal trials were performed in the first part of the experiment. Speed significantly affected the percentage of balls missed in that more balls were missed with increasing ball speed (1 m/s 3.9%, 1.5 m/s 6.0%, and 2 m/s 13.9%). No significant interaction effects were found and the ANOVA that tested for the effect of Target Position and Speed did not reveal any main or interaction effects.

Kinematics: the influence of impact requirements (Goal versus No-Goal)

Table 1 shows for both conditions and each ball speed the means and averaged within-subject standard deviations for all dependent variables.

A significant main effect of speed ($F_{(2,16)} = 3.991$, $P < 0.05$) and a significant Target-by-Speed interaction effect ($F_{(2,16)} = 10.917$, $P < 0.001$) was found for the impact velocity. Post hoc testing revealed that the impact velocity was higher for the ball approaching at 2 m/s than at 1 m/s. However, this effect was solely found in the No-Goal condition. In other words, speed-coupling was exclusively found when the ball was not propelled towards a goal.

With respect to the movement time, a significant interaction effect ($F_{(2,16)} = 4.397$, $P < 0.05$) was also found. Post hoc tests showed that when the participants aimed towards a goal, the movement time did not differ significantly. On the other hand, in the condition where participants did not aim at a goal, the movement time was significantly affected by ball speed. In this condition, the movement time was longer for the balls approaching at 1 m/s than at 2 m/s.

Table 1 Means and averaged within-subject standard deviations (in parentheses) of impact velocity and movement duration for each condition (Goal, No-Goal) and ball speed (1, 1.5, 2 m/s)

	Goal			No-Goal		
	1 m/s	1.5 m/s	2 m/s	1 m/s	1.5 m/s	2 m/s
Impact velocity (mm/s)	2222 (530)	2158 (466)	2228 (461)	2294 (212)	2340 (198)	2481 (215)
Movement time (ms)	266 (63)	279 (59)	270 (57)	253 (42)	248 (33)	230 (30)

Table 2 Means and within-subject standard deviations (in parentheses) for impact velocity and movement time for different target positions (Near-Goal and Far-Goal) and ball speeds (1, 1.5, 2 m/s)

	Near-Goal			Far-Goal		
	1 m/s	1.5 m/s	2 m/s	1 m/s	1.5 m/s	2 m/s
Impact velocity (mm/s)	1737 (181)	1757 (207)	1820 (214)	2674 (260)	2569 (203)	2632 (168)
Movement time (ms)	313 (50)	321 (36)	314 (42)	223 (33)	235 (42)	226 (28)

Kinematics: the influence of target position (Near-Goal versus Far-Goal)

An overview of means and averaged within-subject standard deviations for the near and far goal for each ball speed is given in Table 2.

For the impact velocity ($F_{(1,8)}=220.409$, $P<0.001$) and the movement time ($F_{(1,8)}=137.506$, $P<0.001$) there was a significant main effect of Target Position. Balls that had to be propelled to a further goal were hit with a larger impact velocity and shorter movement duration. For impact velocity, the ANOVA also revealed a significant Target Position-by-Speed interaction effect ($F_{(2,16)}=6.705$, $P<.01$). The Tukey tests indicated that when participants aimed for the near goal the impact velocity for balls approaching at 2 m/s was larger than for balls approaching at 1 and 1.5 m/s. For the far goal, the impact velocity was generally smaller for trials with ball speed of 1.5 m/s than for trials with ball speeds of 2 m/s and 1 m/s. No interaction effect was found for movement time.

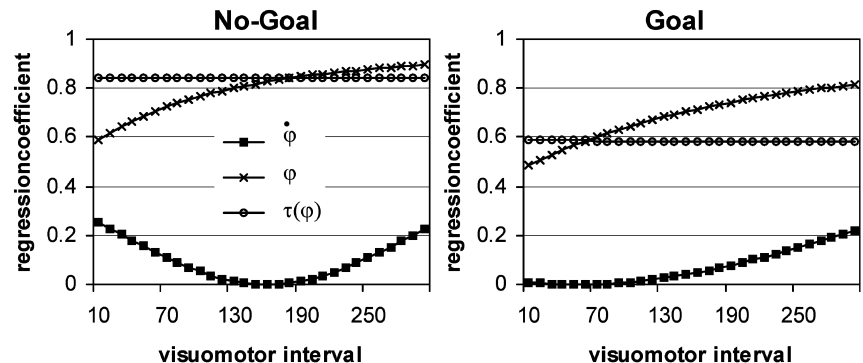
Information sources

It is important to be clear about the type of process that is hypothesized to be controlling the timing in order to make an inference about the information used to regulate the swing. One conceivable strategy is that a critical value of an optical variable that co-varies with the time-to-interception is used to trigger the initiation of a preprogrammed interceptive movement of constant duration (i.e. the operational timing strategy; Tyldesley and Whiting 1975). The observation in the present experiment that movement time varies with ball speed and task requirements such as target position is qualitatively not in agreement with the triggering of a stereotyped movement on the basis of information specifying time-to-contact.

Other proposed control laws assume that optical information may also trigger a non-stereotyped movement (cf. Tresilian 1997). Any optical source may be used to trigger the initiation of a swing followed by parameterization or continuous guidance of the swing. A continuous strategy has the advantage that an action is still adaptive after movement onset. This perspective shifts the attention from a perceptual account, based on the estimation of time-to-contact and the triggering of a preprogrammed movement with a fixed duration, to a more flexible dynamic account based on a continuous coupling of movement to information (e.g. Schöner 1994; Peper et al. 1994; Dessing et al. 2002). Of particular importance is that a continuously controlled action can be initiated on the basis of a critical value of an information source as well. Hence, our search for those critical values of informational sources used to regulate the onset of the swing does not presuppose a completely predictive strategy.

To determine the information sources that exerted influence on the onset of the swing we quantitatively assessed the relation between the time-evolution of three optical sources (i.e. φ , $\tau(\varphi)$, and $\dot{\varphi}$) and the observed patterns of swing onset. Figure 3 provides the calculated regression coefficients between velocity and each of the three optical sources [φ , $\tau(\varphi)$, and $\dot{\varphi}$] at each visuo-motor interval for participant De. The left panel shows the results for hitting the ball without impact constraints (i.e. No-Goal) and the right panel shows the results for hitting the ball towards a goal (i.e. Near-Goal and Far-Goal). The plot reaches a region of non-significant regression coefficients for $\dot{\varphi}$, but not for φ and $\tau(\varphi)$. A non-significant regression coefficient indicates that the values of $\dot{\varphi}$ did not differ significantly for the three ball approach speeds. So, this participant might have regulated the onset of the hit on basis of $\dot{\varphi}$. Note that the area of convergence differs for the

Fig. 3 Regression coefficients of the regressions between three informational variables and ball approach speed for visuomotor intervals of 0–275 ms for hit onset. The *right* panel shows the results for goal-directed hits (Goal) and the *left* panel shows the results for hits without impact constraints (No-Goal) for participant De



two conditions. The convergence was found to be earlier for goal-directed hits (bandwidth 50–110 ms, minimum at 60 ms) than for hits without any impact constraints (bandwidth 80–250 ms, minimum at 160 ms).

Table 3 presents the estimated best-converged-upon values of the optical variables [φ , $\dot{\varphi}$, and $\tau(\varphi)$] for the smallest non-significant r^2 -values and the bandwidth of converged-upon values for which the r^2 -values were non-significant, as well as the matching visuo-motor intervals.

In addition, Table 3 also summarizes for all participants the r^2 - and P -values of the minimum non-significant regression coefficients between ball approach speed and the values of φ , $\dot{\varphi}$, and $\tau(\varphi)$. Where the coefficient of variation of a particular variable exceeded the 25% level (*asterisk* in Table 3), the inference that movement onset was regulated on basis of this value was made less reliable. A striking result is that none of the participants showed critical regions for optical values other than $\dot{\varphi}$. For hits

Table 3 The r^2 - and P -values (s denotes a significant regression coefficient) of the smallest non-significant regression coefficient for the regressions between the optical variables φ , $\dot{\varphi}$ and $\tau(\varphi)$, and ball

approach velocity and the best-converged-upon values (and bandwidth, in *parentheses*) of the optical variables with matching visuo-motor intervals (VMI)

Participant	Optical variable	No-Goal				Goal			
		r^2	P	Value (rad/s)	VMI (ms)	r^2	P	Value (rad/s)	VMI (ms)
De	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.99	0.13 (0.17–0.10)	160 (80–250)	0.001	0.94	0.17 (0.18–0.14)	60 (50–110)
Es	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.91	0.15 (0.20–0.12)	140 (60–210)	0.001	0.96	0.22 (0.22–0.16)	10 (0–140)
Ka	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.98	0.07 (0.09–0.05)	260 (150–370)	0.001	0.91	0.14 (0.16–0.11)	60 (0–140)
Lo	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.92	0.21 (0.21–0.15)	10 (0–100)	0.002	0.90	0.19 (0.19–0.15)	20 (0–80)
Mo	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.99	0.22 (0.23–0.17)	20 (0–90)	—	s	—	—
Pi	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.91	0.10 (0.12–0.07)	170 (90–260)	0.001	0.88	0.17 (0.16–0.14)	10 (0–110)
Ra	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.92	0.12 (0.16–0.09)	110 (90–260)	0.013	0.36	0.17 (0.17–0.15)	10 (0–60)
Ru	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.94	0.10 (0.14–0.07)	260 (160–380)	0.001	0.86	0.18 (0.18–0.14)	10 (0–90)
Sj	$\tau(\varphi)$	—	s	—	—	—	s	—	—
	φ	—	s	—	—	—	s	—	—
	$\dot{\varphi}$	0.001	0.99	0.15 (0.20–0.11)	90 (0–180)	0.001	0.82*	0.16 (0.16–0.12)	10 (0–90)

*Coefficient of variation of that particular variable increased beyond the 25% level

without impact constraints all participants showed highly non-significant regression coefficients for $\dot{\varphi}$ (P -values ranging from 0.91 to 0.99) with visuo-motor intervals ranging from 10 to 260 ms (mean 135.6 ms). For hits with impact constraints eight out of ten participants showed non-significant regression coefficients for $\dot{\varphi}$. Note, however, that for participant Sj the coefficient of variation was found to be too large ($>25\%$).

So, in general seven participants showed a clear area of convergence for $\dot{\varphi}$ in the Goal condition. These seven participants showed non-significant regression coefficients for $\dot{\varphi}$ (P -values ranging from 0.86 to 0.96) with visuo-motor intervals ranging from 10 to 60 (mean 23.75 ms). A paired t -test on the best converged-upon values of $\dot{\varphi}$ and matching visuo-motor intervals showed for the seven participants a significant decrease in visuo-motor interval ($t_{(6)}=-4.224$, $P<0.01$) and an increase in the critical value ($t_{(6)}=3.161$, $P<0.05$) of $\dot{\varphi}$ found in the conditions Goal and No-Goal.

Intuitively it could be expected from the kinematic results that a different optical variable underpinned the different timing strategies found for the Goal condition (i.e. no ball speed effect on hit onset) compared with the No-Goal condition (i.e. ball speed effect on hit onset). However, the time-evolution of $\dot{\varphi}$ showed that the same optical variable can account for the different timing patterns. Figure 4 illustrates that for a critical region around 0.08 rad/s the onset of the hit occurs shorter before contact in response to faster approaching balls; this is in agreement with the timing pattern we found for hits without imposed impact requirements. Note however, that a qualitatively different timing pattern occurs for a critical region around 0.16 rad/s. Under these circumstances the differences in onset for the three velocities disappeared (i.e. become indiscernible) and this is exactly what we found for the goal-directed hits.

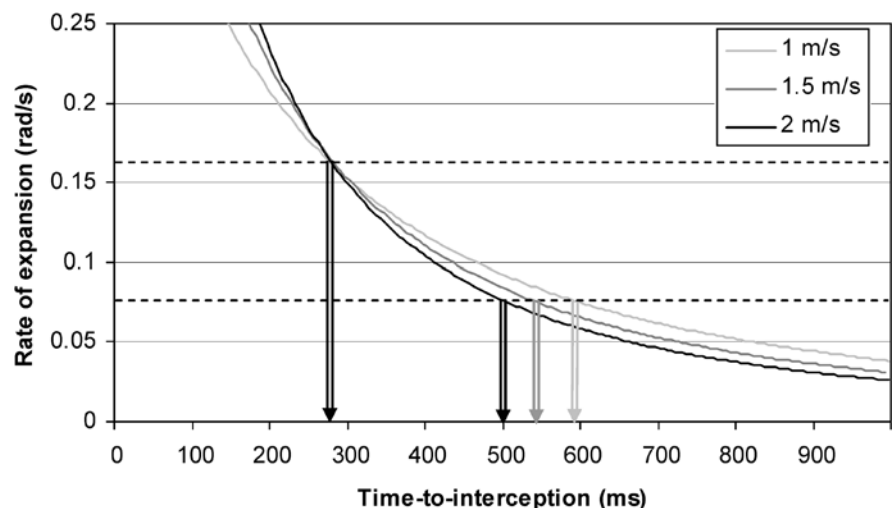
Discussion

We investigated the capacities of participants to perform one-dimensional hitting movements in the frontal plane to balls approaching on a head-on collision course. Since the interception point and the initial position of the effector were the same in all trials the emphasis was on temporal regulation, in particular the initiation of the movement. First, we manipulated the time-window for the interceptive movement by varying the ball speed. We did so to examine the influence of imparted task-constraints by the demanded temporal precision of the task. Second, we manipulated the force applied to the ball at contact by enforcing the distance to be covered by the ball after contact. We were particularly interested in the information used to regulate the initiation of the movement and, specifically, how the information-based regulation changes in consideration of task-constraints.

The results of the first part of the experiment (i.e. without imposed impact requirements) showed that participants moved faster (as measured by impact velocity) when the time-window was smaller and hence the temporal precision higher. This is in agreement with previous studies that decreased the time-window by manipulating the size of the hitting effector, or the size of the approaching object or the speed of the approaching object (Tresilian and Lonergan 2002; Tresilian et al. 2003). Mason and Carnahan (1999) pointed out that under severe time constraints viewing time is a more important determinant of movement time, and therefore movement velocity, than projectile approach speed. From this viewpoint it is important to note that in the present experiment target travel-time constraints do not play an important role, because the viewing time is much longer (1–2 s) than the movement time (between 230 and 290 ms).

The findings also reveal that the timing was clearly affected by ball speed in that participants initiated at a longer time before contact in response to slower approaching balls. The quantitative analyses showed for all participants that a viable explanation for the observed

Fig. 4 The time-evolution of the rate of expansion for the three approach speeds of the ball. Horizontal dashed lines represent the hypothesized critical values and vertical arrows depict the matching time-to-interception for each ball speed. A critical value of 0.08 rad/s is reached at a shorter time-to-interception for faster approaching balls. This would result in an earlier initiation for the 2 m/s ball speed compared to the 1 m/s condition. On the other hand, for a critical value of 0.16 rad/s no difference in timing would occur



onset patterns of the swing is a regulation on basis of a critical value of the absolute rate of expansion. The variable $\dot{\varphi}$ has gained support in previous interceptive studies where approach velocity or size was varied (Smith et al. 2001; Michaels et al. 2001; Caljouw et al. 2004).

Note however that any variable co-varying with $\dot{\varphi}$, such as for example the rate of change of binocular disparity, could do the job as well. The capability to regulate initiation on the basis of correlates of expansion velocity must have its origin in brain processes that extract this information from the visual environment. Lappe (2004) described in a review of the biological foundation of time-to-contact that the primate brain has neuronal sensitivity for both rate of expansion and rate of change of binocular disparity. It is obvious from the above that our current knowledge of the neural mechanisms is in agreement with the behavioural data and we may conclude that expansion velocity as well as rate of change of binocular disparity might contribute to the initiation of interceptive actions.

The second part of the experiment investigated goal-directed hits. We studied the effect of variations in force applied by the effector to the ball on the initiation of the swing by presenting goals at different distances. When the movement path is kept constant, the only way to increase the force at the moment of impact is to decrease the movement time, and hence to increase the velocity at impact. As expected, impact velocity at the moment of ball contact was high when participants aimed for a far goal compared to a near goal. Regarding the temporal characteristics of the movement, results showed that movement duration decreased with increasing distance to the goal. In other words, participants increased the force applied to the ball by postponing the moment of initiation and increasing movement velocity.

In the present experiment there is a bottleneck for the speed effects observed in the first part of the experiment and the impact requirements imposed in the second part of the experiment. Without impact constraints a fast ball induces high movement velocity and hence high impact velocity. This might contradict with low impact task constraints such as the requirement to propel the ball towards a near goal. So, it seems improbable that participants would retain speed-coupling when hitting the ball towards a goal. In the second part of the experiment we indeed observed no significant ball speed effect on the timing. We found, under the circumstances that impact requirements were imposed, a constant movement duration, irrespective of the approach speed of the ball.

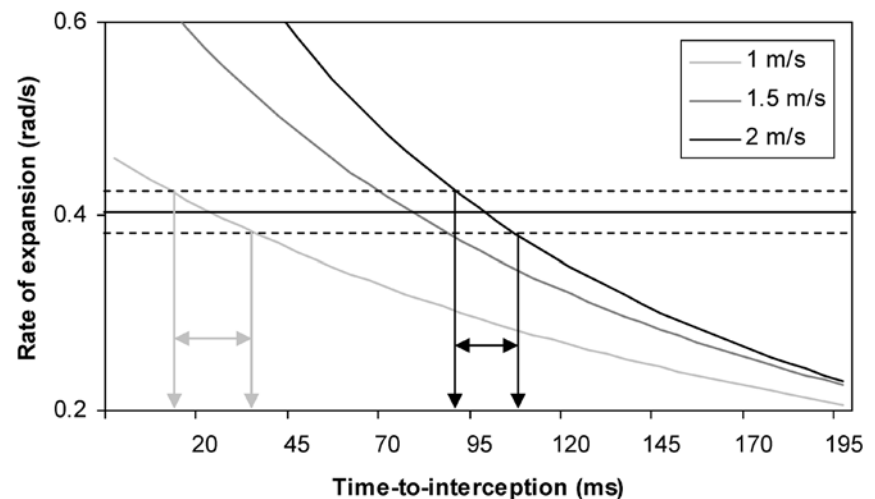
Some researchers may intuitively associate the finding of constant movement durations in interceptive actions with regulation based on optical variables specifying the time-to-interception. This is due to the implicit reasoning that the detection of information about an event entails the perception of this event, and it is the perception of this event that regulates the action. In the literature, information sources can be found that specify the time-to-contact (i.e. TTC) of the ball with the point of observation, such as

$\tau(\varphi)$. Although the results in part two of the present experiment reveal a constant movement duration of the swing irrespective of the approach speed of the ball, $\tau(\varphi)$ cannot be used to regulate the timing of the swing, since interception occurs in front of the observation point. Observers might correct the value of the optical variable $\tau(\varphi)$ to regulate interception in front of the observation point; however, this would implicate a contribution of position or velocity information about the approaching ball. Following this reasoning, observers would have to rely heavily on constructive processes such as inference in order to hit a ball. It is more parsimonious to assume that any optical variable that is in some way confined to the approach of the ball may be used to regulate the initiation of the swing. The timing of swing initiation in part one of this experiment was consistent with a regulation based on $\dot{\varphi}$. Although this optical variable does not relate one-to-one to the time-to-interception, it is not necessarily a useless variable. The detection of such a variable can yield an onset of the swing that is accurate enough to intercept the ball despite the fact that the actor does not perceive the time-to-interception.

In the present experiment we aimed to assess whether adaptation to new task constraints is provided by a change in the nature of the information sources used to support the initiation of the hit or by a recalibration of the way in which an information source is used to regulate the onset. The results of part one showed a specific relation between the optical source $\dot{\varphi}$ and the initiation of the swing. By means of quantitative analyses of the optical source $\dot{\varphi}$ in part two of the experiment we showed that the timing of swing onset was still consistent with a regulation based on $\dot{\varphi}$, in spite of the different task-circumstances. It was found that participants adjusted both the critical value and visuo-motor interval (i.e. the control law) in order to flexibly adapt to the new task constraints. The exploitation of $\dot{\varphi}$ can account for the different timing patterns found in the Goal and No-Goal conditions of this experiment, and for the corollary of speed effects. The time-evolution of $\dot{\varphi}$ for the three velocities reveals that, dependent on the critical value, different timing patterns can arise (see Fig. 4).

If we assume that $\dot{\varphi}$ is also continuously used to temporally regulate the ongoing movement, we can predict several observed phenomena in previous studies regarding the temporal precision of interceptive actions as well. As we already pointed out, speed-coupling has been interpreted to induce the temporal precision necessary for success in intercepting balls of different speeds (e.g. Brouwer et al. 2000; Tresilian and Lonergan 2002, Tresilian et al. 2003). However, the time-evolution of $\dot{\varphi}$ for the three velocities can provide an alternative explanation for the increased temporal precision that is associated with faster approaching balls. Inspection of Fig. 5 shows that the change over time (i.e. the slope of the

Fig. 5 The time-evolution of the rate of expansion for the three approach speeds of the ball. Horizontal lines depict a value of $\dot{\varphi}$ (solid line) with a variation around it (dashed lines). Arrows depict the resulting bandwidth of variation in timing for slow (grey arrows) and fast (black arrows) approaching balls. A similar absolute variation around a value of $\dot{\varphi}$ results in a large temporal variability when the approach speed of the ball is slow compared to fast



lines) increases with ball speed. If $\dot{\varphi}$ is also continuously used to temporally regulate the ongoing movement we would predict that a small variation (i.e. noise) around the value of $\dot{\varphi}$ results in a large bandwidth of temporal variability when the approach speed of the ball is slow compared to fast (represented by arrows in Fig. 5). So, speed-coupling per se is not necessarily a strategy that is adopted in order to regulate the temporal precision. Changes in temporal accuracy can as well be explained from the time-evolution of optical variables such as $\dot{\varphi}$ used to regulate interceptive actions. In other words, the increased temporal precision for faster ball speeds may be information-based. Another phenomenon frequently observed in interceptive actions is the increase in temporal accuracy of a goal-directed movement as it is performed (e.g. Savelsbergh et al. 1991; Bootsma and Van Wieringen 1990). A close look at the time-evolution of $\dot{\varphi}$ shows that the change over time increases up to the moment of impact. As a consequence, an absolute variation around a small value of $\dot{\varphi}$ (i.e. in the first part of the ball path) results in a large variation in timing compared with that stemming from a similar absolute variation around a large value of $\dot{\varphi}$ (i.e. in the final part of the ball path). In sum, the exploitation of $\dot{\varphi}$ or any co-varying variable can account for the timing patterns of movement onset and structural changes in temporal precision frequently observed in interceptive movements to balls approaching with different velocities.

The present results revealed different critical regions for $\dot{\varphi}$ depending on task constraints such as hitting towards a goal or not. Much of the research on delays between stimulus and response has traditionally emphasized the fixed nature of neural transmission times; however, we anticipate that the interval over which a control law operates is more variable. The accepted neurophysiological perceptual-motor delay is 100 ms, but for different interceptive tasks longer and shorter visuo-motor intervals

are reported (Bootsma and Van Wieringen 1990; Brenner and Smeets 1997; Michaels et al. 2001). In our opinion, such a visuo-motor interval can take many values depending on whether attention is already directed to the information that will guide the action, on the nature of the information, or on the goal of the actor. Knowledge of the cerebellar circuitry suggests that it is involved in predicting the consequences of actions and might therefore be used to overcome time delays associated with the sensory inflow of information (for a review see Mauk et al. 2000; Wolpert et al. 1998; Desmurget and Grafton 2000). So, the cerebellum might shunt responses to an appropriate time depending on the task at hand. In our study, participants adjusted the moment of initiation relative to the moment at which the threshold value of the involved optical variables was reached depending on the presence of impact requirements. Thus, it might be possible that the participants exploited the visuo-motor interval to comply to different task-constraints.

Our results imply that the adaptation of timing patterns to the task-constraints in this experiment is not provided by a change in the nature of optical information sources used to time the initiation of the swing but is realized by an adjustment in the critical value and visuo-motor interval of the same optical information source, that is, the absolute rate of expansion or any co-varying variable.

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